Simulating Transonic Buffet Aerodynamics for the Boeing Transonic Truss-Braced Wing Aircraft

Oliver M. F. Browne*, Daniel Maldonado, Jeffrey A. Housman, and Jared C. Duensing

Computational Aerosciences Branch

NASA Ames Research Center

William E. Milholen

Configuration Aerodynamics Branch

NASA Langley Research Center

Session: FD-03: RANS / LES / Hybrid Methods: Applications

AIAA 2024 SciTech Forum, Orlando, Florida

January 8th, 2024

*Science and Technology Corp.

Outline

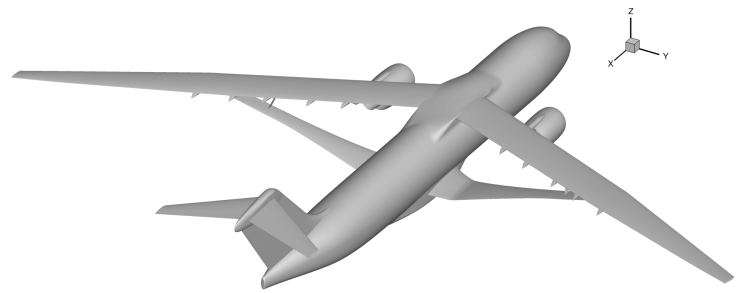
- Motivation
- Numerical Framework and Meshing Approach
- M=0.8 TTBW Results
  - Aerodynamic loads and surface pressure
  - Power spectral density (PSD)
- Conclusions

Outline

- Motivation
- Numerical Framework and Meshing Approach
- M=0.8 TTBW Results
  - Aerodynamic loads and surface pressure
  - Power spectral density (PSD)
- Conclusions

Boeing Transonic Truss-Braced Wing

- Transonic Truss-Braced Wing (TTBW) concept is a design that NASA and Boeing are collaborating to develop which has the potential to improve fuel efficiency for commercial aircraft.
- The thinner and truss-braced wing has a longer span and reduced wing sweep compared to conventional airliners which can reduce the amount of drag originating from wing tip vortex formation (*i.e.* drag due to lift) and the smaller wing chord would allow for natural laminar flow control to be employed to reduce friction drag.
- TTBW includes a high aspect ratio wing, in addition to wing and jury struts, leads to complex flow phenomena such as transonic buffet, shock induced separated flow, and a turbulent wake.



Transonic buffet is an instability characterized by self-sustained low-frequency oscillations of the shock on the upper surface of the wing which arises when there is shock induced boundary-layer separation due to interactions between the shock and the turbulent boundary-layer. This can result in unsteady loading on the aircraft wings which can cause fatigue failure.

Boeing Transonic Truss-Braced Wing

- Fig (right) shows the new 9% scale semi-span model of the Subsonic Ultra Green Aircraft Research (SUGAR) M=0.8 TTBW configuration mounted in the test section of the NASA Ames 11-by 11-Foot Transonic Wind Tunnel.[1]
- The tunnel testing covered a broad range of test conditions with a Mach number range of 0.20 – 0.92 and a mean chord Reynolds number range of 2.2×10^6 to 6.58×10^6.
- WT model was instrumented to record aerodynamic load/moments, static surface pressure (taps) and unsteady pressure (Kulites).
- In this work, we investigate the free air configuration with CFD for M=0.8 and Re=5.2M and compare to corrected set of WT results. A modified wing-fuselage fairing is utilized (developed by Boeing) to ensure the semi-span model would adequately replicate the spanwise lift distribution, including the location of the inboard wing shock wave.

[1]Harrison, N. A., Sclafani, A. J., Cerra, D., Dickey, E. D., Patel, D., Straccia, J., Vijgen, P., Crouch, J., Otto, C., Loh, K.-C., and Jones, A., "Subsonic Ultra Green Aircraft Research: Phase V - Buffet Test Report," NASA CR–2023-XXXXXX, NASA, 2023.

Scale Resolving Simulations for Buffet Prediction

- High Lift Prediction Workshop 4 (HLPW4) further highlighted that steady-state RANS approaches struggle to accurately predict the aerodynamic loads at CL,max when there were large regions of separated flow on the wing.
  - Scale-resolving simulation approaches such as wall-modelled Large-Eddy Simulations (WMLES) and hybrid RANS/LES (HRLES) showed more promise and tended to predict CL,max within the 2% accuracy requirement proposed within Certification by Analysis (CbA).
- Within the framework of CbA, it is stipulated:
  - that the unsteady aerodynamic loads need to be computed including the effect of separated flows and shock/boundary-layer interactions
  - Predict buffet onset within a speed of 3 knots of the validation data.

  At the very least this would require unsteady RANS (URANS) simulations or, more likely, moving towards time accurate scale-resolving simulations to fulfill this criteria.
- Transonic buffet on both 2-D airfoils (NACA0012, OAT15A) and 3-D wings (High-Speed Common Research Model) has been studied with both HRLES and WMLES (see paper for refs). Generally, both approaches show improvements over steady-state RANS computations,
- HRLES studies that employed Delayed Detached Eddy Simulations (DDES) have shown a tendency to predict the shock further upstream than experiment and a larger separated region behind the shock. Several authors have proposed modifications to the HRLES shielding function (see paper for refs).

Outline

- Motivation
- Numerical Framework and Meshing Approach
- M=0.8 TTBW Results
  - Aerodynamic loads and surface pressure
  - Power spectral density (PSD)
- Conclusions

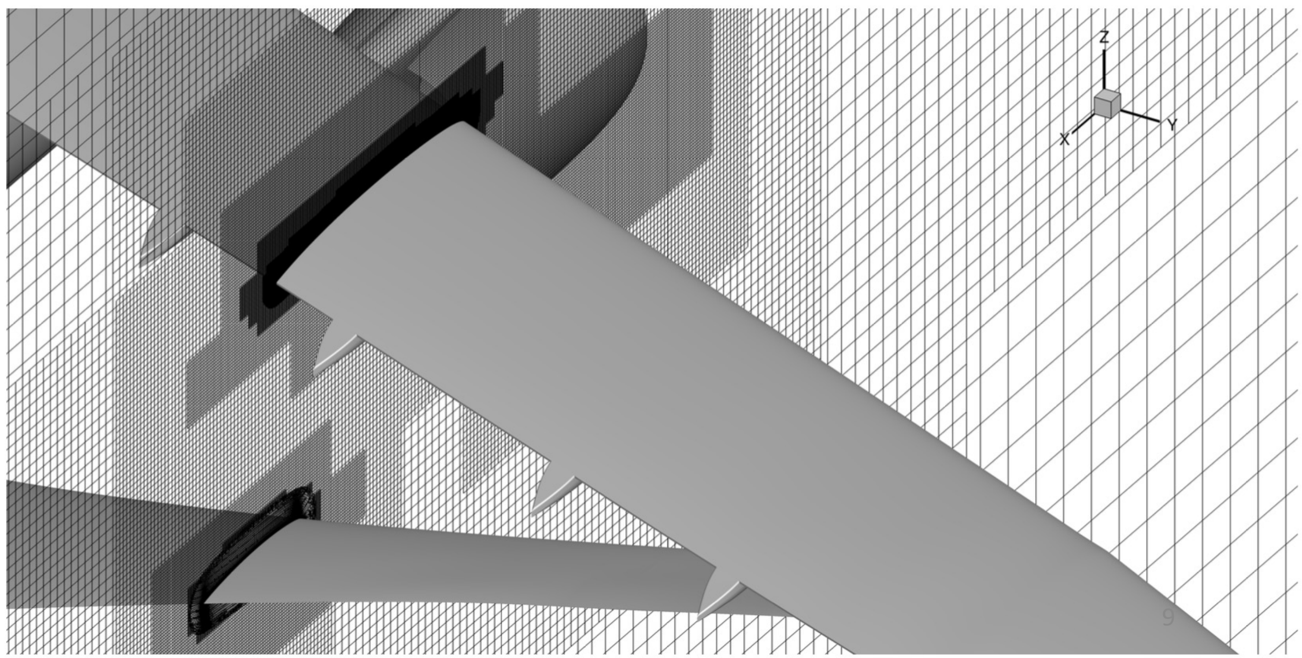
LAVA DDES Discretization

- Compressible Reynolds Averaged Navier-Stokes (RANS) equations.
- Curvilinear Structured Overset Mesh Topology.
- Convective Scheme – Hybrid Weighted Compact Nonlinear Scheme (HWCNS), blended third-order upwind/fourth-order centered accurate scheme, WENO limiting, standard HLL numerical flux.
- Time Integration – implicit BDF2 time-stepping, 3-4 orders of residual convergence at each time-step.
- Underlying Turbulence Model – SA-neg with with corrections: LRe - low Reynolds number and CC – compressibility correction
- Shielding Function – ZDES2020 Mode 2 Enhanced Protection (Deck & Renard 2020), maximum cell edge length use as local length scale in LES SGS closure.

Curvilinear Overset Grid System

- Three grid levels considered: coarse, medium and fine.
- Coarse to medium is a global refinement (1.4x) whereas medium to fine is refining (2.8x) on upper surface of the main wing only.
- Sensitivity studies with respect to time-step size and including a wake mesh on the wing and strut were performed.

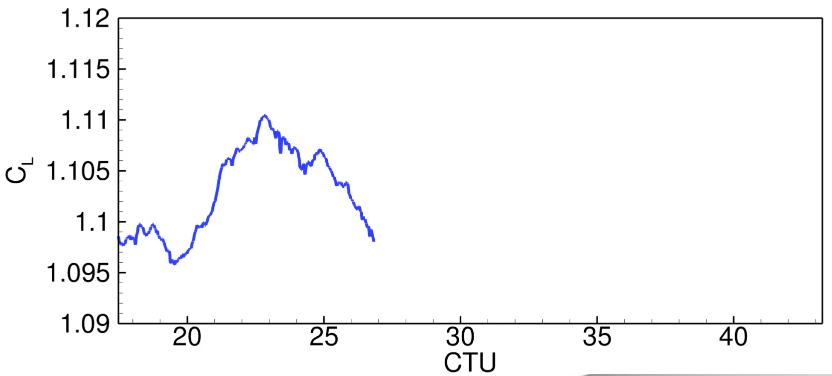
Name	Solve Points	Wing Upper Surface Δx at $0.5x/c$ (mm)	Wing Upper Surface Δy at $0.5x/c$ (mm)	Wing Upper Surface Stretching Ratio	Target y^+	Δt (s)
Coarse	99.3M	0.024	0.024	1.25	1.0	1e-4
Medium	228.9M	0.0176	0.0176	1.12	1.0	7.14e-05
Fine	397.3M	0.0083	0.0083	1.085	1.0	5e-5



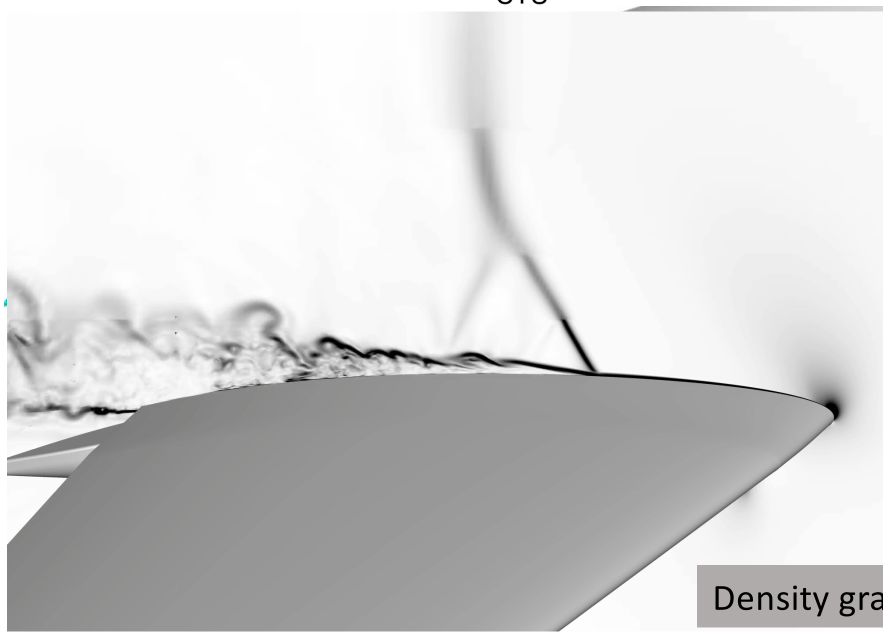
Outline

- Motivation
- Numerical Framework and Meshing Approach
- M=0.8 TTBW Results
  - Aerodynamic loads and surface pressure
  - Power spectral density (PSD)
- Conclusions

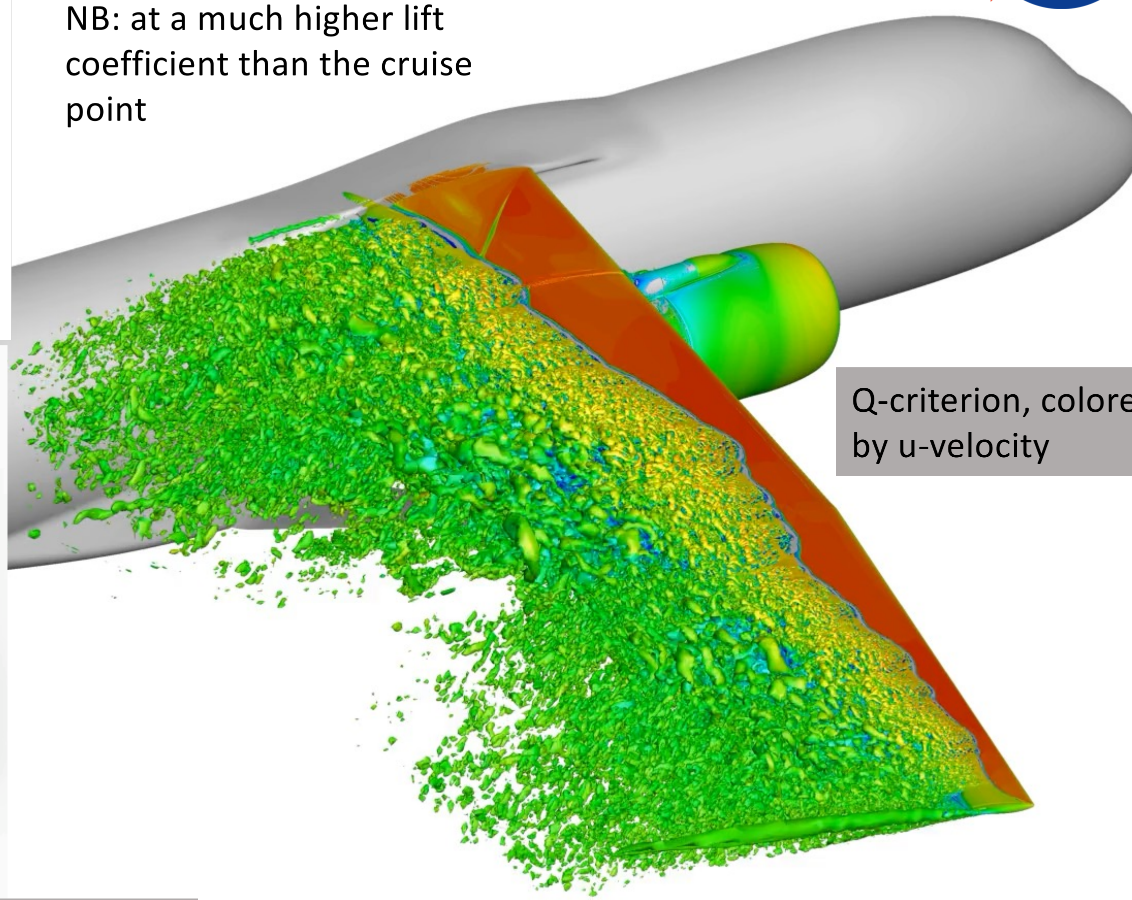
Flow Visualization, M=0.8 and α=5.0°



NB: at a much higher lift coefficient than the cruise point



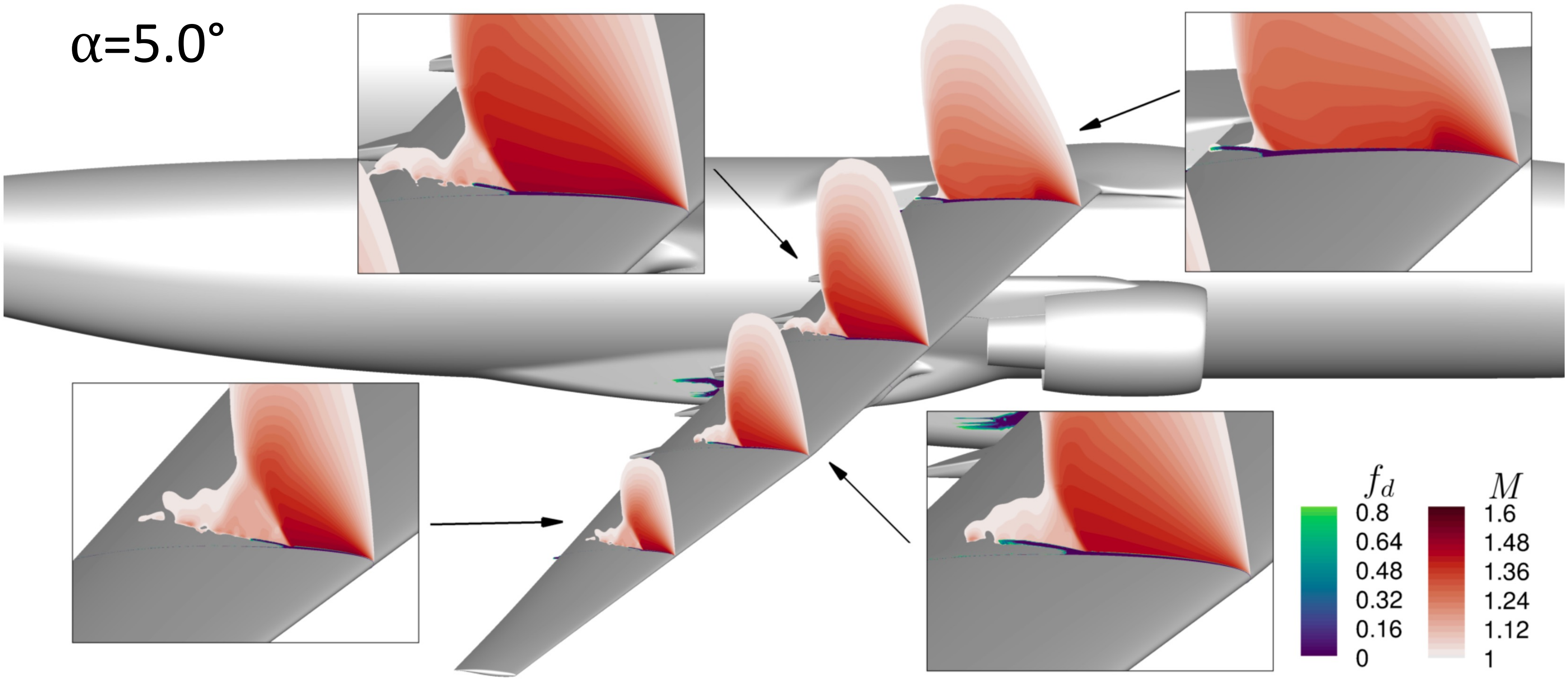
Density gradient mag.



Q-criterion, colored by u-velocity

Shielding Function, f_d, Behavior

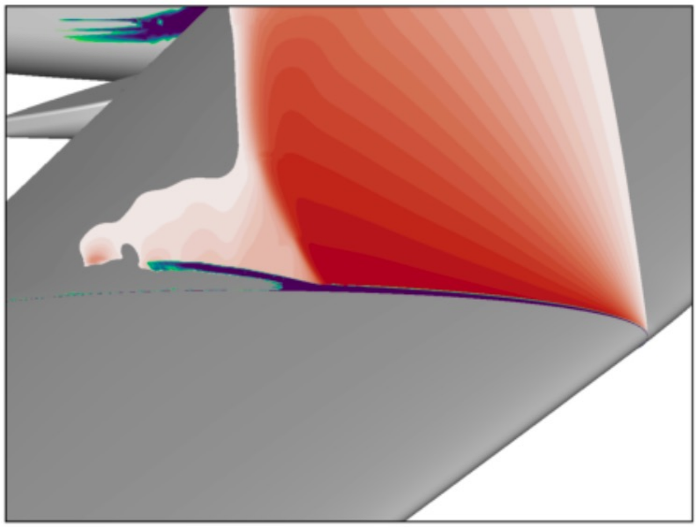
α=5.0°

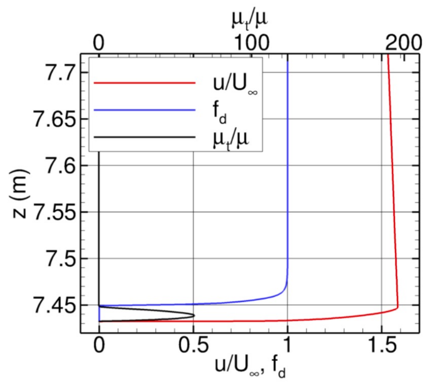


- Instantaneous contour slices of shielding function and local Mach number at four stations along the wing span.
- There appears to be a lambda shock structure forming on the wing upper surface.

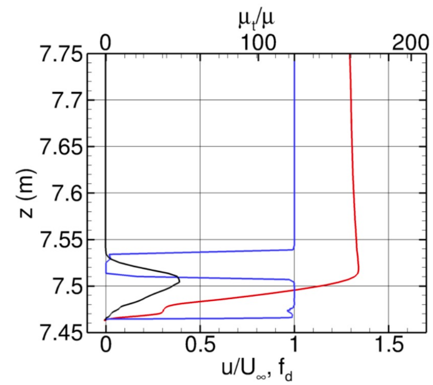
Shielding Function, f_d, Behavior

α=5.0°

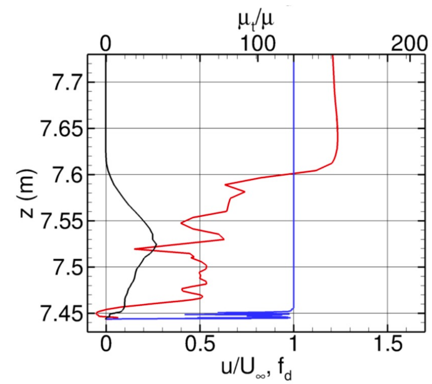




(a) $x/c = 0.242$



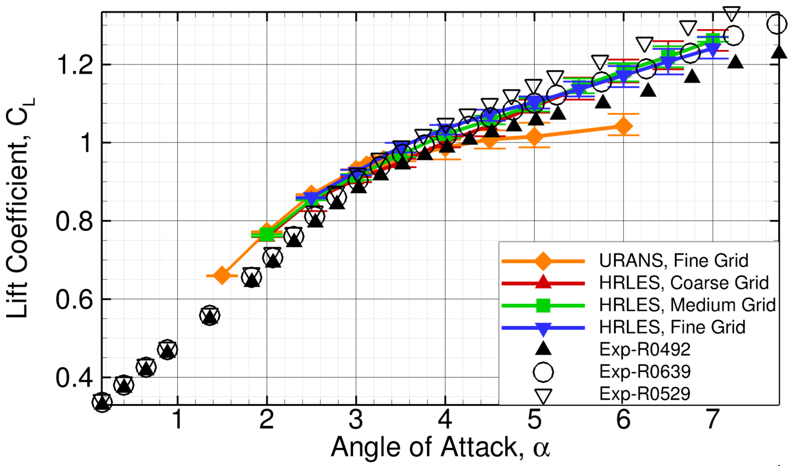
(c) $x/c = 0.485$



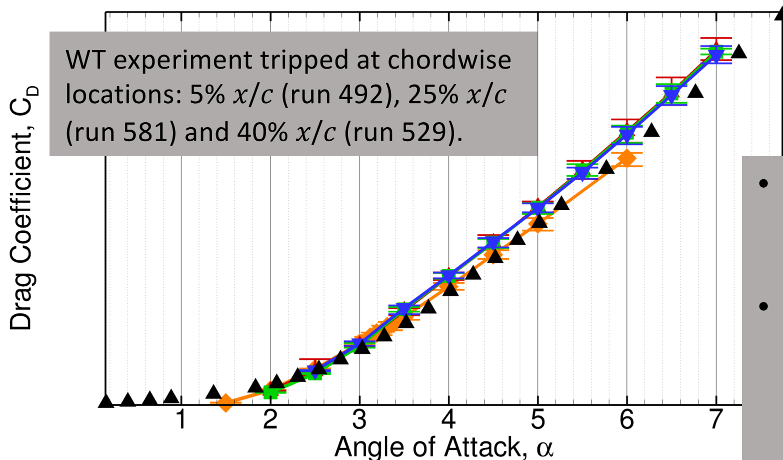
(e) $x/c = 0.714$

- Boundary layer is protected in RANS mode upstream of the shock, once the boundary layer separates the flow is in LES mode.

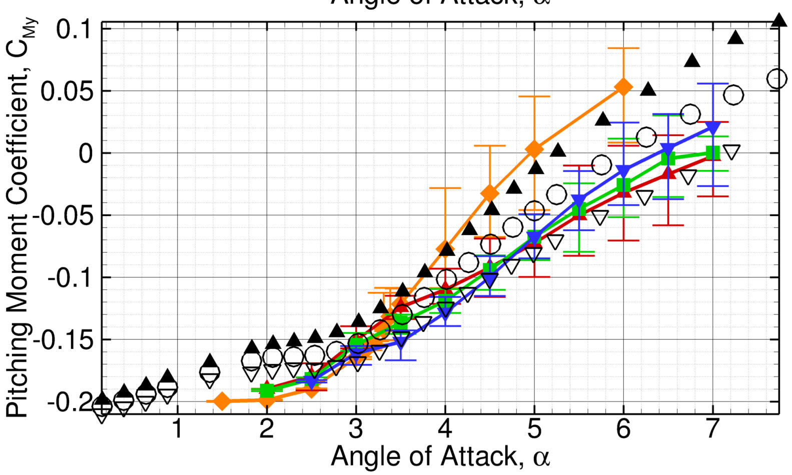
Aerodynamic Loads, M=0.8 and Re=5.2M

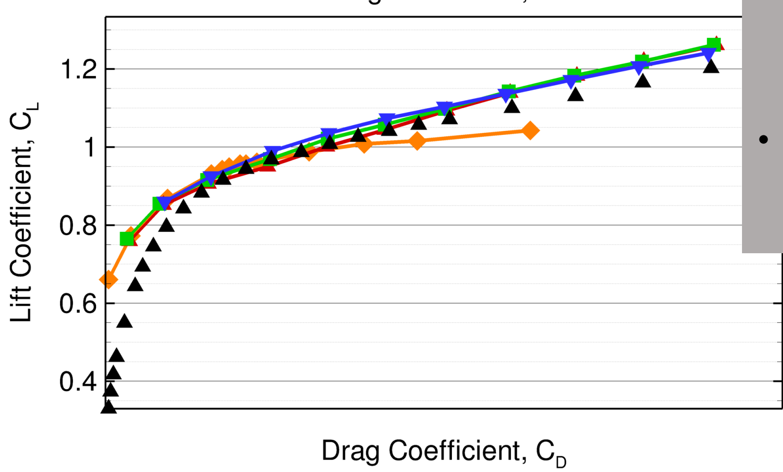


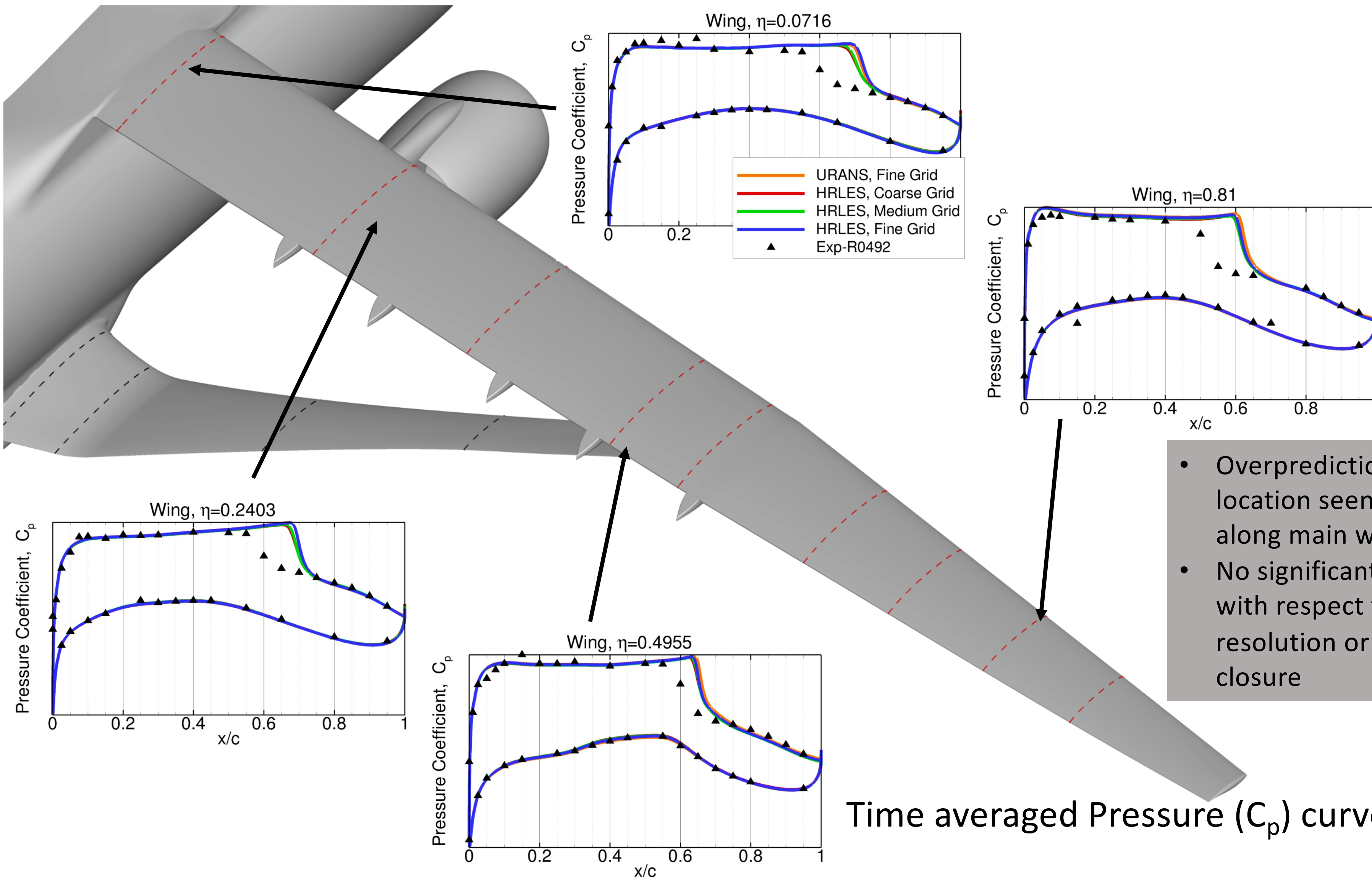
WT experiment tripped at chordwise locations: 5% x/c (run 492), 25% x/c (run 581) and 40% x/c (run 529).



- URANS and HRLES overpredict lift at angles-of-attack pre pitch-break.
- HRLES shows a lift curve at the post pitch-break angles-of-attack that shows best agreement with 25% x/c tripped case. Relatively small sensitivity to grid resolution observed in lift.
- HRLES shows underprediction in pitching moment across angle-of-attack sweep

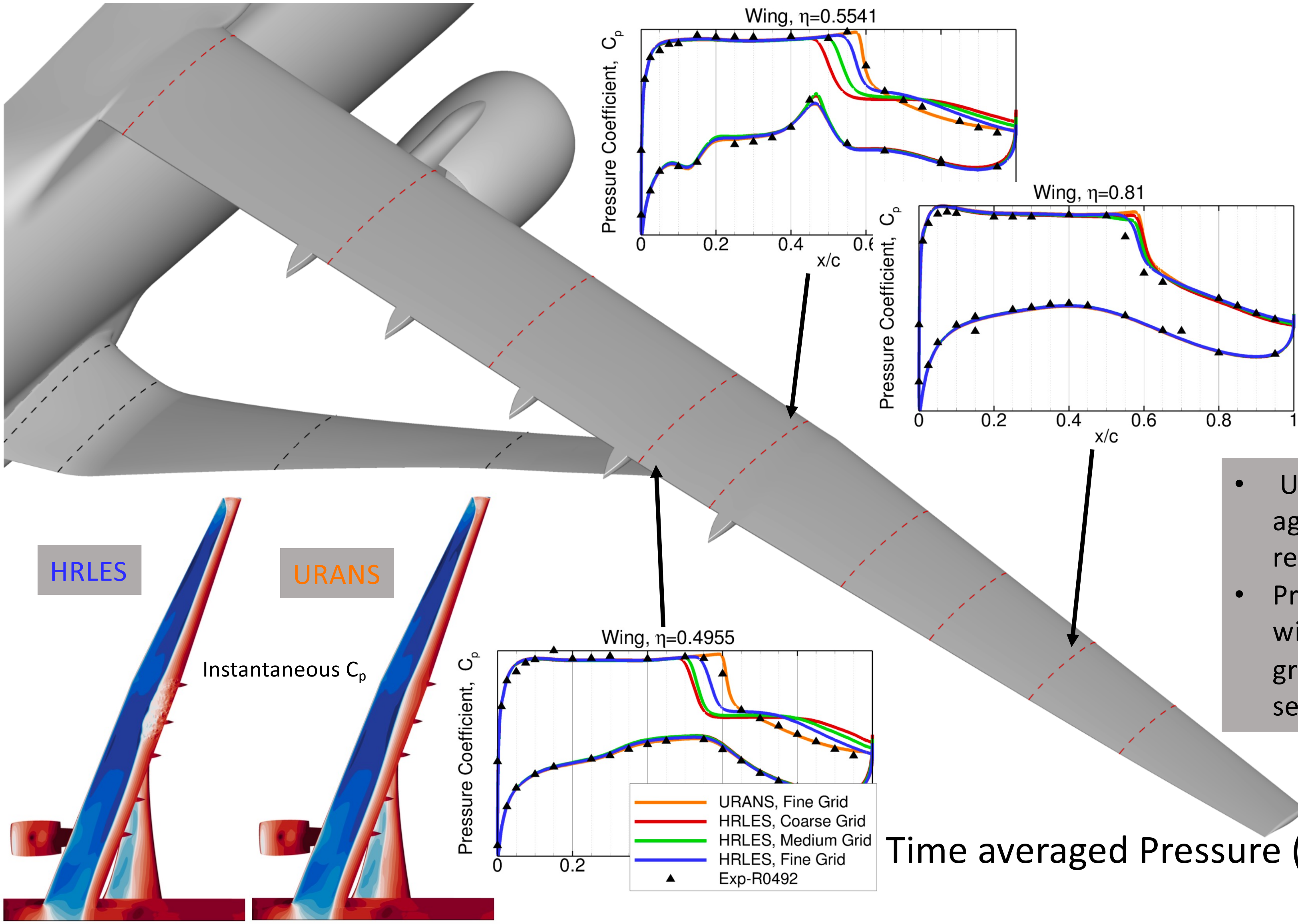






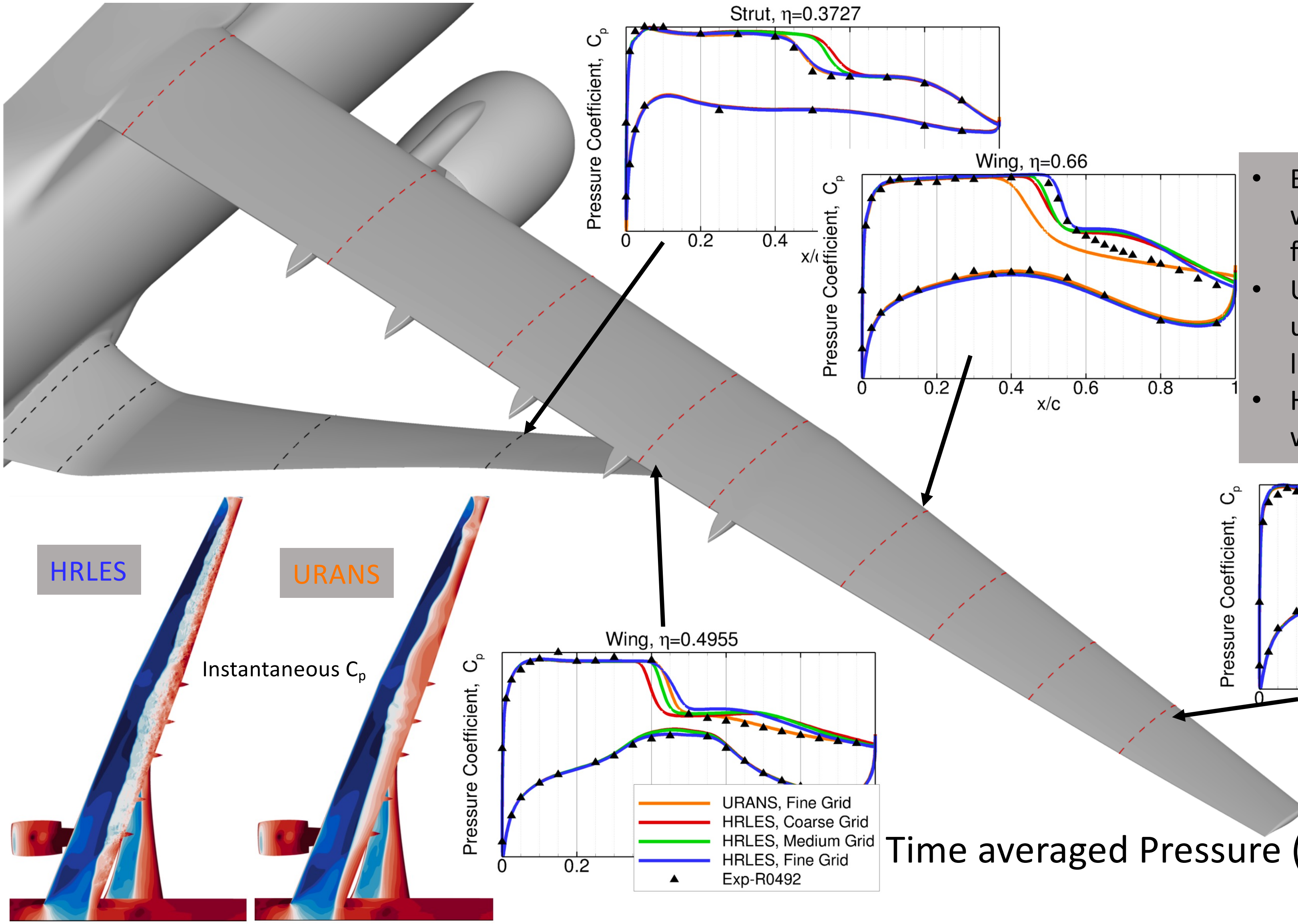
- Overprediction of shock location seen at all stations along main wing span
- No significant sensitivity with respect to mesh resolution or turbulence closure

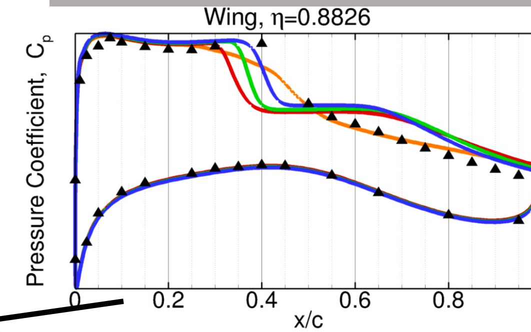
Time averaged Pressure (C_p) curves, α=2.5°



- URANS shows good agreement with exp. results,
- Predicted shock location with HRLES is sensitive to grid resolution, plateau seen behind shock,

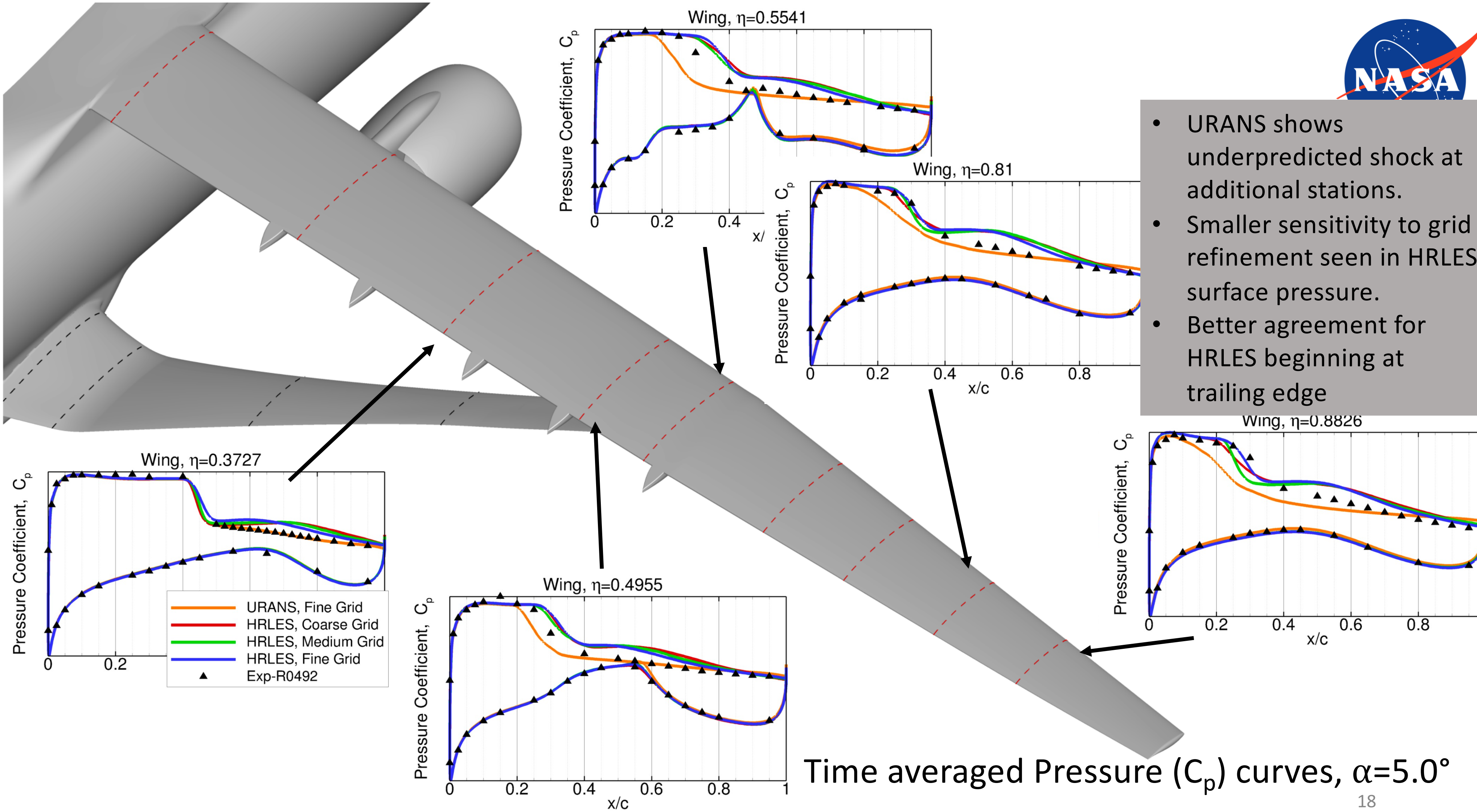
Time averaged Pressure (C_p) curves, α=3.0°





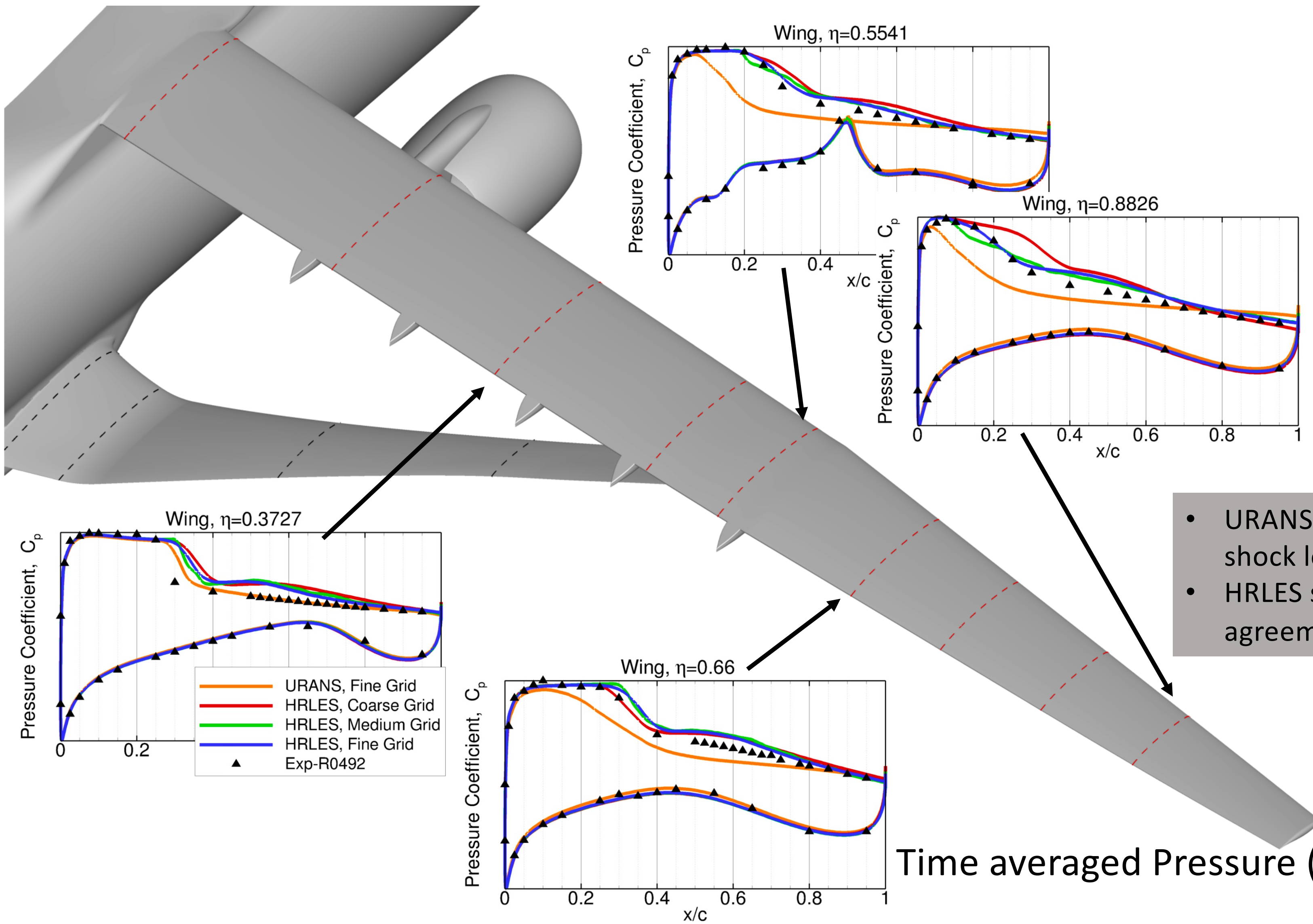
- Better agreement on strut with HRLES and URANS on fine grid
- URANS begins to underpredict shock location at η=0.66.
- HRLES shows improvement with grid refinement

Time averaged Pressure (C_p) curves, α=4.0°



- URANS shows underpredicted shock at additional stations.
- Smaller sensitivity to grid refinement seen in HRLES surface pressure.
- Better agreement for HRLES beginning at trailing edge

Time averaged Pressure (C_p) curves, α=5.0°

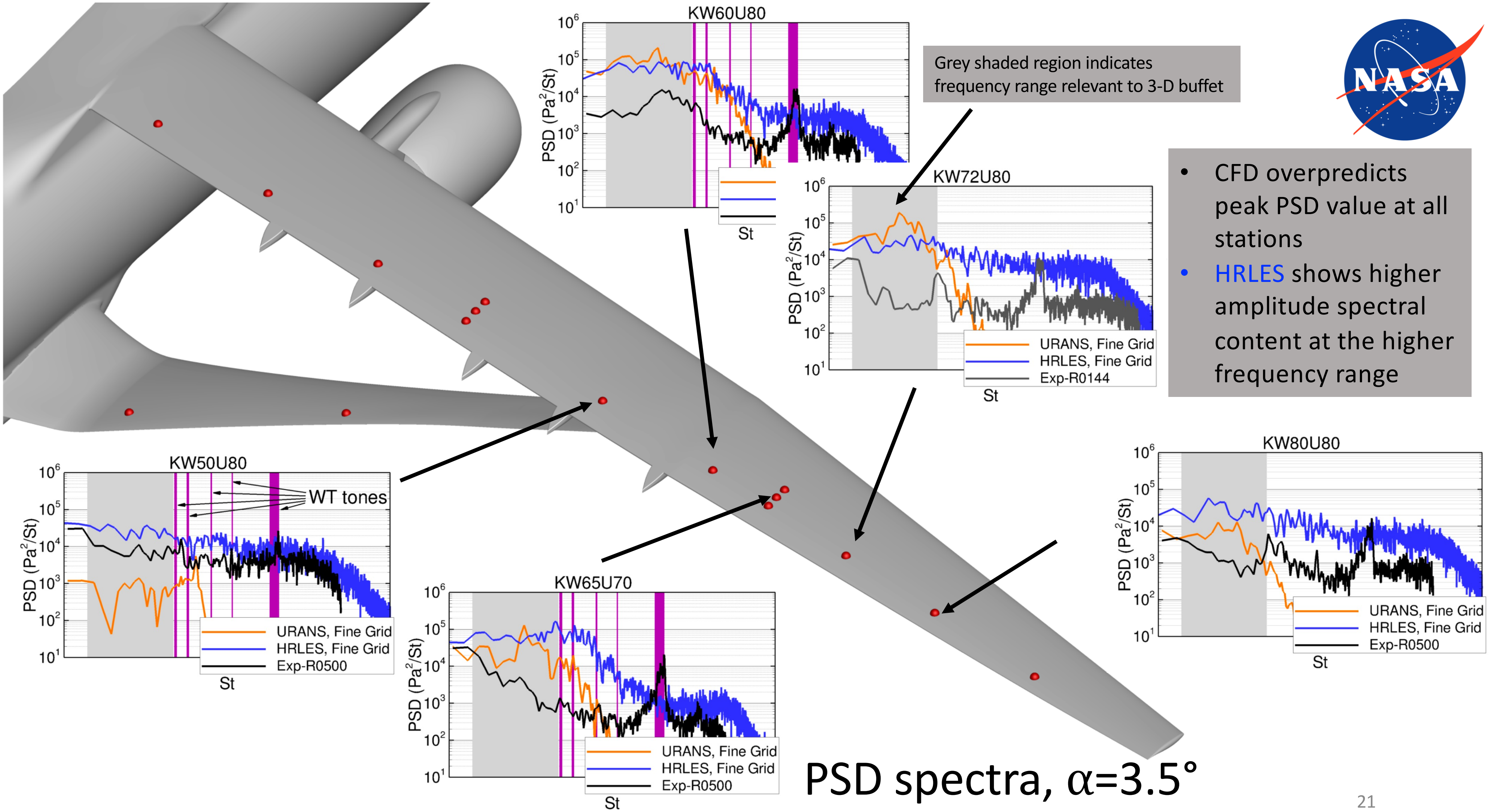


- URANS severely underpredicts shock location,
- HRLES showing better agreement with experiment

Time averaged Pressure (C_p) curves, α=6.0°

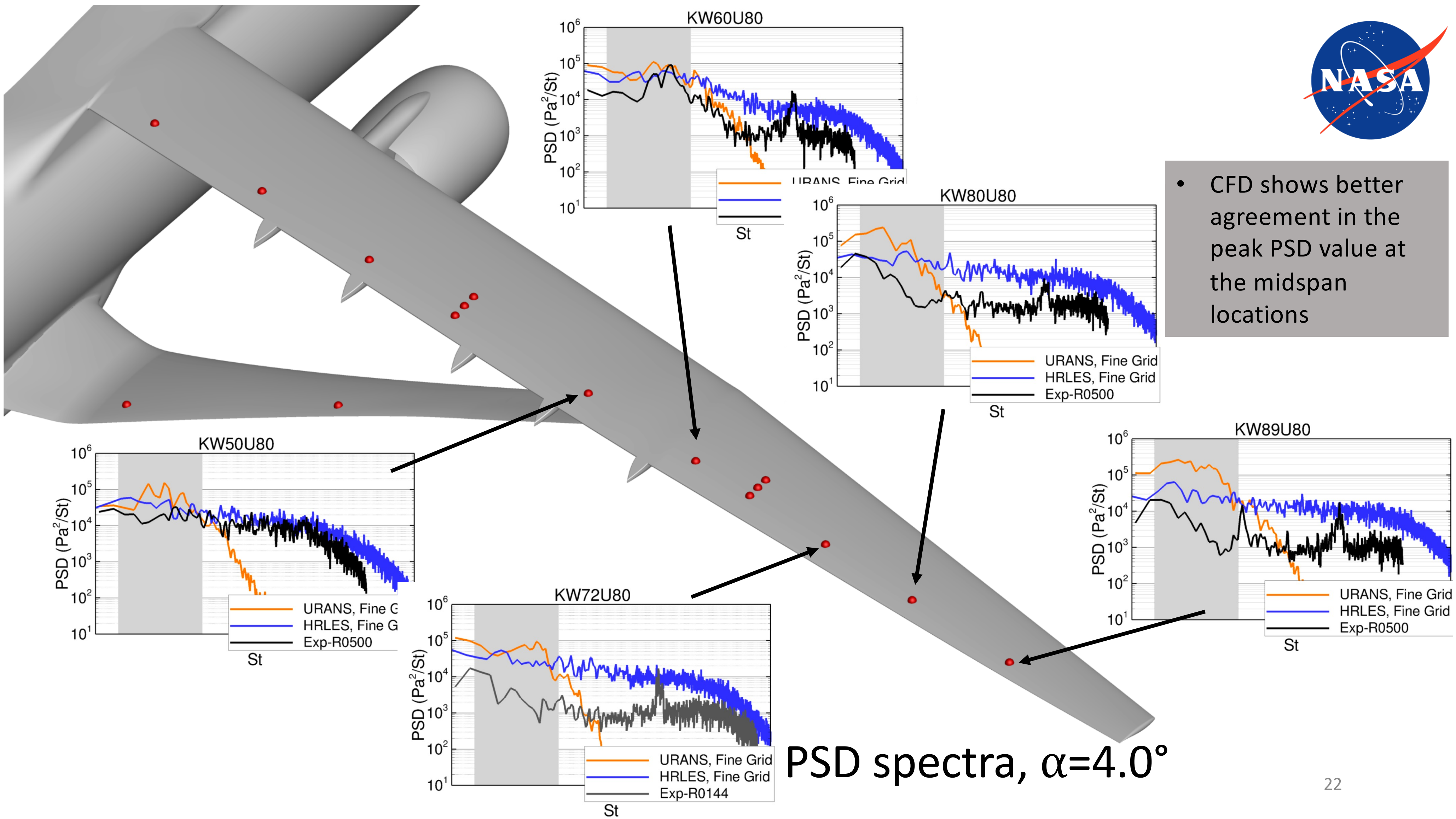
Outline

- Motivation
- Numerical Framework and Meshing Approach
- M=0.8 TTBW Results
  - Aerodynamic loads and surface pressure
  - Power spectral density (PSD)
- Conclusions



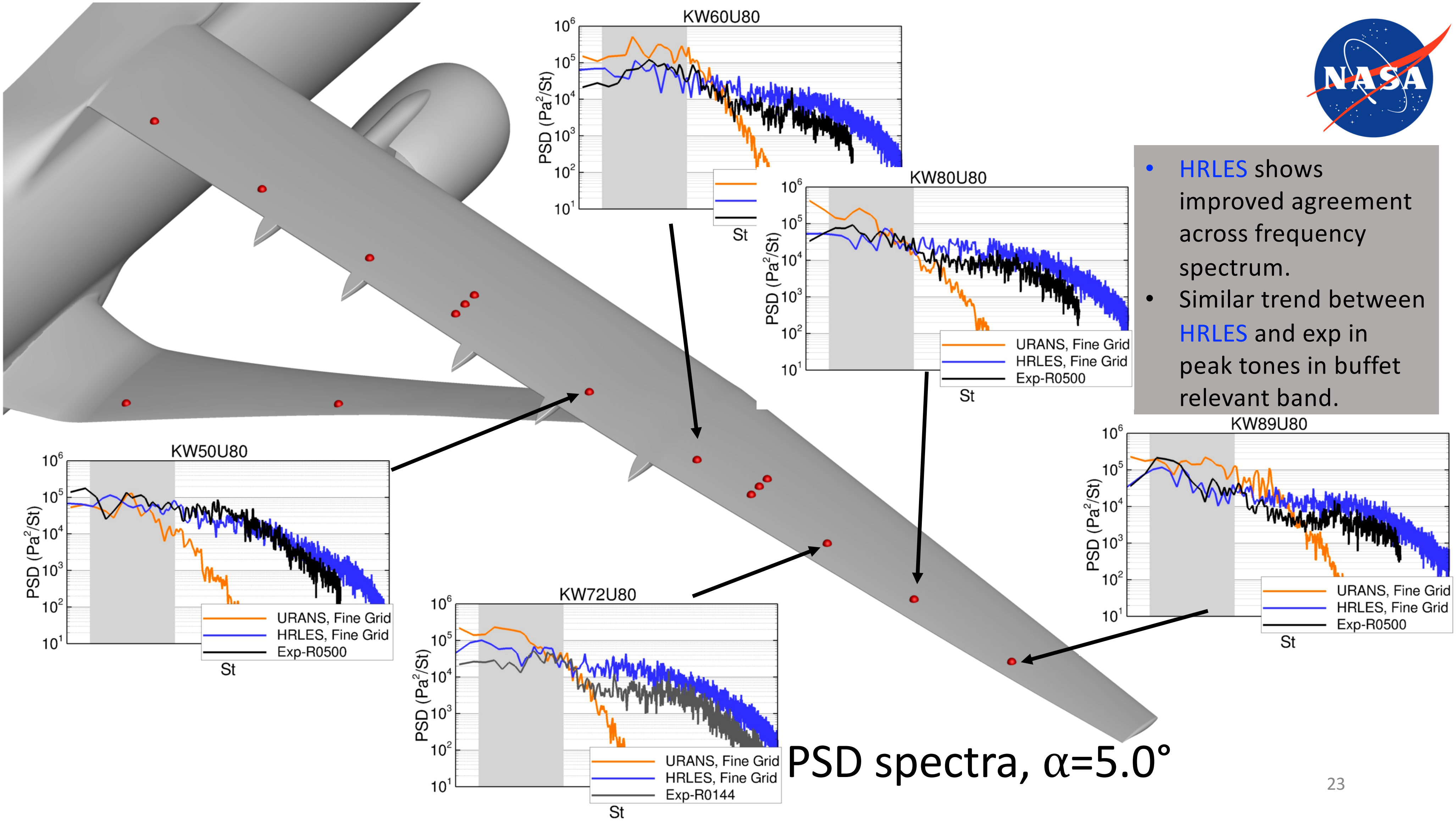
- CFD overpredicts peak PSD value at all stations
- HRLES shows higher amplitude spectral content at the higher frequency range

PSD spectra, α=3.5°



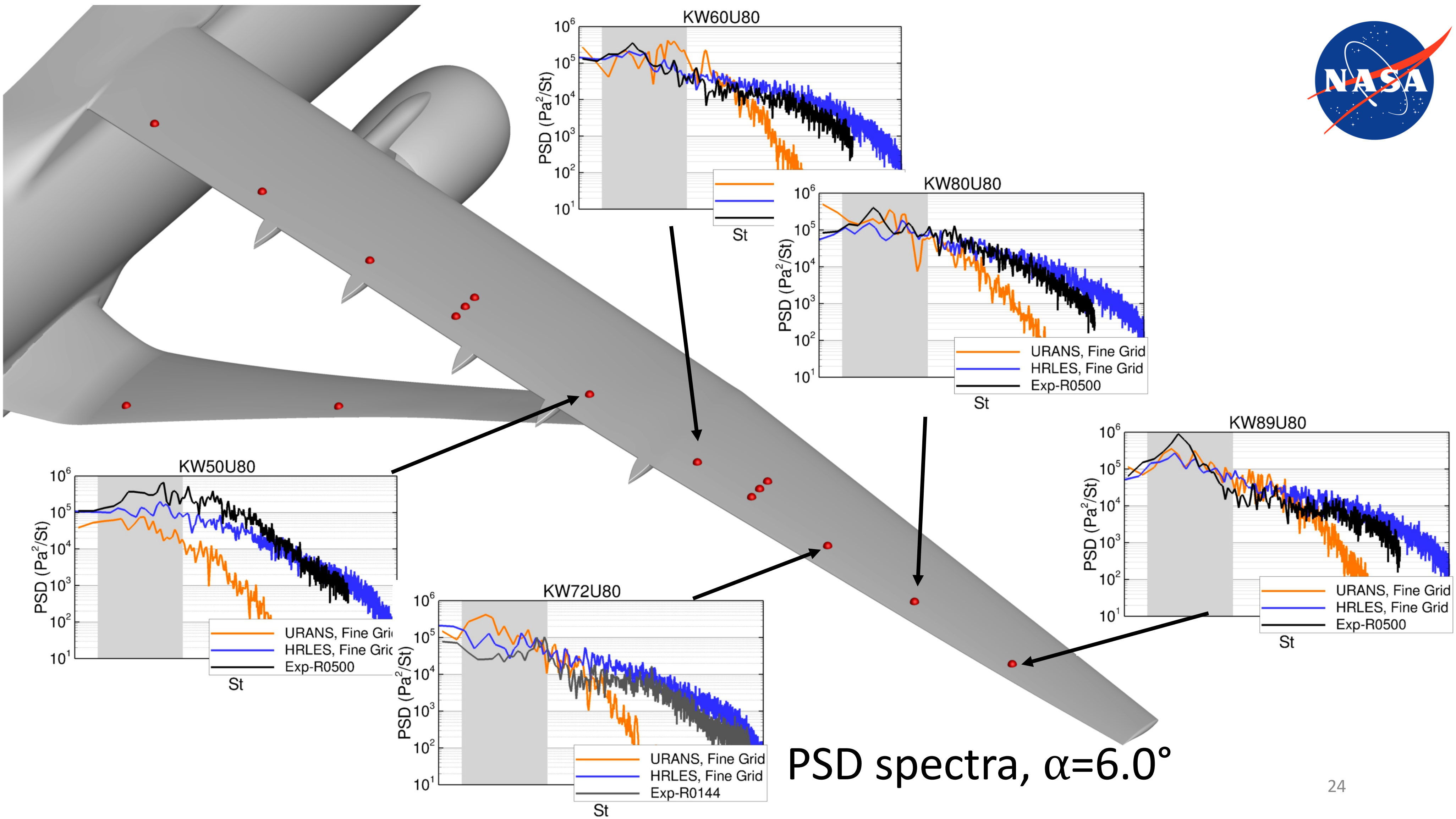
- CFD shows better agreement in the peak PSD value at the midspan locations

PSD spectra, α=4.0°

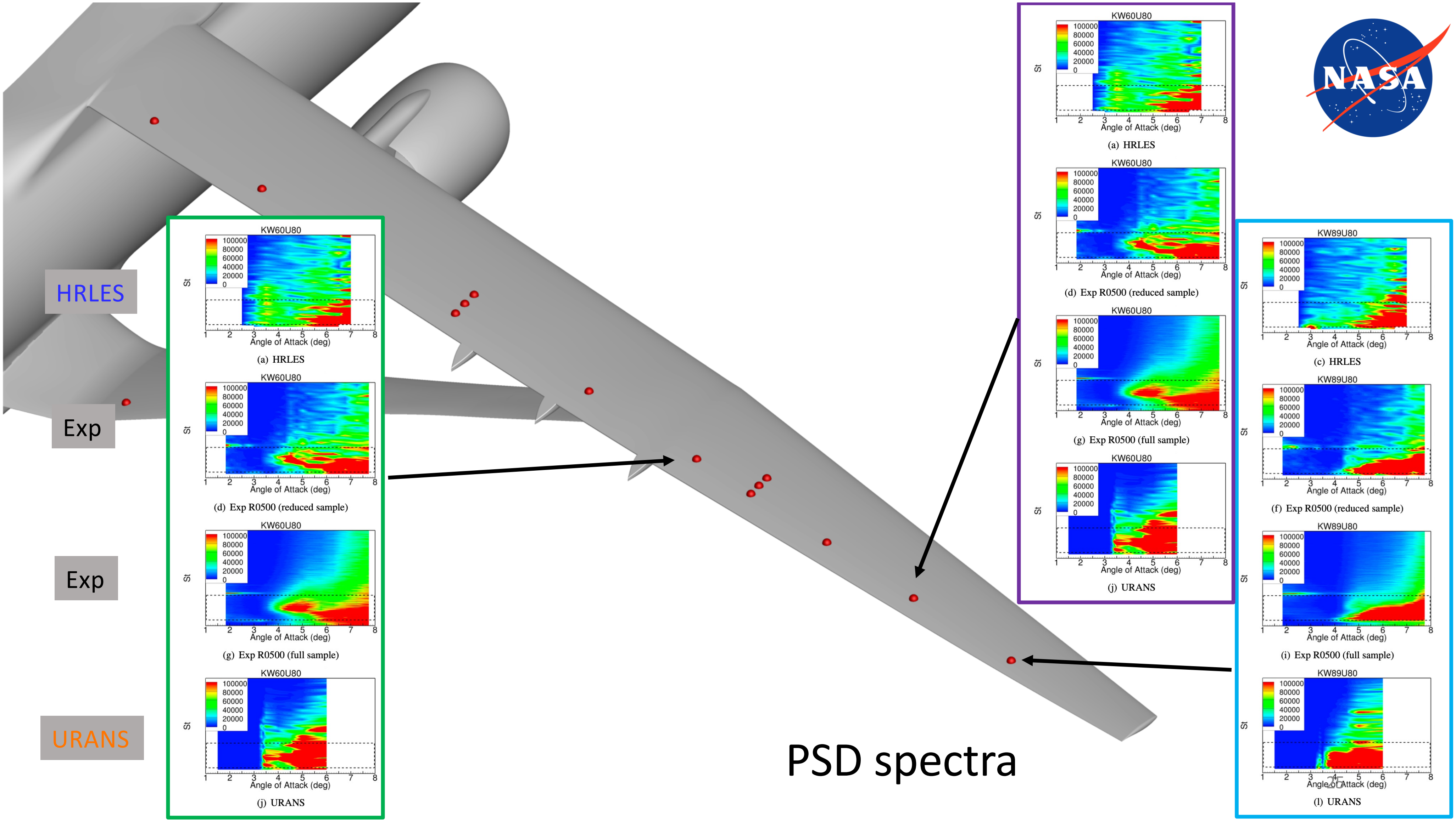


- HRLES shows improved agreement across frequency spectrum.
- Similar trend between HRLES and exp in peak tones in buffet relevant band.

PSD spectra, α=5.0°



PSD spectra, α=6.0°


HRLES
Exp
Exp
URANS
PSD spectra
KW60U80
(a) HRLES
(d) Exp R0500 (reduced sample)
(g) Exp R0500 (full sample)
(j) URANS
KW89U80
(c) HRLES
(f) Exp R0500 (reduced sample)
(i) Exp R0500 (full sample)
(l) URANS
St
Angle of Attack (deg)
100000
80000
60000
40000
20000
0

Outline

- Motivation
- Numerical Framework and Meshing Approach
- M=0.8 TTBW Results
  - Aerodynamic loads and surface pressure
  - Power spectral density (PSD)
- Conclusions

Summary and Conclusions

- Investigated HRLES turbulence modeling approach to predict buffet on TTBW, compared with URANS and experimental data from NASA Ames 11-by 11-Foot TWT,
- Aerodynamic loads predicted by HRLES show reasonable agreement with the experiment with a slight overprediction of the lift and drag seen compared to the 5% x/c tripped case,
- HRLES shows an improved prediction of the shock location with grid refinement at the angles-of-attack post pitch-break. However, there is a plateau in the pressure immediately behind the shock and subsequently an underprediction in pressure rise.
- Onset of buffet appears to originate in the mid-span region of the main wing based on the instantaneous surface pressure contours and the PSD data. HRLES shows generally good agreement with the PSD data, particularly in the frequency range that is associated with transonic buffet instability modes. URANS tends to overpredict the peak PSD value when compared to experiment. Both HRLES and URANS predict the onset of buffet at around 0.5° earlier than the experiment, based on the PSD curves.

Future Work

- Further work is required to determine if when moving to finer grids, HRLES will continue to improve the agreement of the predictions compared to the experiment with regards to reducing the separated flow region.
- A high fidelity model of the in-tunnel environment will also be needed to compare with the uncorrected in-tunnel angles-of-attack and if buffet can be predicted under those conditions.
- Finally, during the experiment, at some of the higher angles-of-attack there was observable flutter particularity in the outboard region of the wing which is not modeled in the simulations presented in this paper. Incorporating fluid-structure interaction methods into these simulations and running CFD simulations on static deformed girds will be another area of research that will be investigated.

Acknowledgements

- This work was funded by the NASA Advanced Air Transport Technology (AATT) and Transformational Tools and Technologies (TTT) Projects.
- Computer time has been provided by the NASA Advanced Supercomputing (NAS) facility at NASA Ames Research Center.
- The authors appreciated the help of Gregory Zilliac (NASA Ames) and Max Amaya (NASA Ames) with obtaining and discussing the experimental data.
- The authors also appreciated the help of Leonardo Machado (NASA Ames) with reviewing this paper and Francois Cadieux (NASA Ames) with both reviewing this paper and many fruitful discussions. The authors also thank Gerrit Stich (NASA Ames) for providing help with post-processing some of the data.